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ELLIPTIC VOLUME GRID GENERATION FOR VISCOUS CFD PARAMETRIC DESIGN STUDIES

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Abstract

This paper presents a robust method for the generation of zonal volume grids of design parametrics for aerodynamic configurations. The process utilizes simple algebraic techniques with parametric splines coupled with elliptic volume grid generation to generate isolated zonal grids for changes in body configuration needed to perform parametric design studies. Speed of the algorithm is maximized through the algebraic methods and reduced number of grid points to be regenerated for each design parametric without sacrificing grid quality and continuity within the volume domain. The method is directly applicable to grid reusability, because it modifies existing flow adapted volume grids and enables the user to restart the CFD solution process with an established flow field. Use of this zonal approach reduces computer usage time to create new volume grids for design parametric studies by an order of magnitude, as compared to current methods which require the regeneration of an entire volume grid. A sample configuration of a proposed Single Stage-to-Orbit Vehicle is used to illustrate an application of this method.

Nomenclature

I,ξ	streamwise computational direction measured from nose to tail of body
J,η	circumfrential computational direction measured from top to bottom of body
K,ζ	computational direction normal to body surface
K-line	grid line traversing from the body to the outer boundary
i,j,k	computational coordinates of a point
P	blending coefficient in the I-direction
Q	blending coefficient in the J-direction
ΔS_{k}	distance between points (i, j, k) and $(i, j, k-1)$
X, Y, Z	Cartesian coordinates
σ	cell growth scale factor

Introduction

The design process used in defining and constructing most aerodynamic vehicles in the supersonic and hypersonic flight regimes involves parametric studies. These studies explore the sensitivities of geometry changes, freestream conditions, etc. to determine the effects on flight performance. The geometric changes may include variations in airfoil shape, wing camber, slenderness, empennage volume, and control surface orientation.

There are several ways to analyze parametric changes in vehicle shapes, including design engineering tools, wind tunnel testing, and CFD (Computational Fluid Dynamics). Design engineering tools, such as the Supersonic Hypersonic Arbitrary Body (SHAB[1]) program and the Aerodynamic Preliminary Analysis System (APAS[2,3]) may be employed to do parametric studies for aerodynamic vehicles. Such techniques combine empirical and theoretical equations to evaluate flight characteristics. Wind tunnel testing allows for the evaluation of complicated configurations, for which accurate models may be designed and built with the aid of CADCAM (Computer Aided Design and Computer Aided Manufacturing) systems.

For flight conditions that cannot be replicated in a wind tunnel or accommodated in a design engineering tool, CFD becomes an important player in parametric studies. CFD driven parametric studies for the supersonic and hypersonic flight regimes, have become feasi-

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ble with the advent of faster supercomputers and more efficient algorithms such as LAURA[4] and GASP.[5] This approach yields results which are in good agreement with wind tunnel data and provide a bridge from experiment to flight conditions. However, this approach is still costly and time consuming. The expense arises not only from computing and processing numerical flowfield solutions, but also from the need to generate surface and volume grids for each parametric change.

Multiple Disciplinary Optimization (MDO) analyses have used parametric studies for several years, with approximate methods being used to evaluate the trends of parametric studies.[6,7] The trends are only part of the parametric analysis. Flowfield and flow structure perturbations resulting from parametric changes are not typically available in a MDO environment. Although trends in hypersonic aerodynamic and thermodynamic performance can be screened by MDO and Euler analyses,[8,9] more detailed computations are required for the assessment of vehicle control surface effectiveness and thermal environment, both of which are viscous dominated flowfield phenomena. Hence, Navier-Stokes computations are required to evaluate the effects of parametric changes of vehicle control surfaces.

Several points must be addressed before a viscous CFD solver may be employed for parametric studies of detailed geometries:

1) Fine grids are required near vehicle surfaces to resolve viscous effects while minimizing the overall number of points in volume grid.
2) It is highly advantageous to avoid separate full configuration CFD solutions for each parameter change.
3) Grid adaption can significantly improve efficiency and accuracy.
4) Grid orthogonality near the vehicle surface improves boundary condition and turbulence modeling accuracy.

This paper addresses these points and outlines a method of grid generation for parametric viscous CFD studies. This technique utilizes elliptic volume grid generation for enhanced control of grid-line incidence angles at all boundaries, as well as near viscous spacing at the wall boundary and enables the use of generic surface types for defining the geometry. The method isolates a region around the parametric part that will change, such that the inflow or interface boundaries to that region are predominantly supersonic.[10] Geometry changes are accomplished using the isolated domain boundary curves at the wall as the defining grid point distributions for the new wall grid edges, and swapping the existing wall surface with a new one. The new surface grid is then generated by attaching the grid to the new definition surface. The parametric volume grid is constructed elliptically, blended with the original volume grid, and initialized with the original CFD solution. Utilization of this method reduces the cost of performing parametric studies with CFD by offering detailed analyses in a timely manner.

Computational Orientation

The coordinate system used in this paper is illustrated in Fig. 1. As shown, the I (or ξ)-coordinate increases from the nose to tail, the J (or η)-coordinate increases from the top to the bottom of the vehicle and K (or ζ)-coordinate increases from the geometry surface to the outer boundary. Throughout this paper, the grid lines that follow the K-direction will be referred to as K-lines (where I and J are constant for a given K-line).

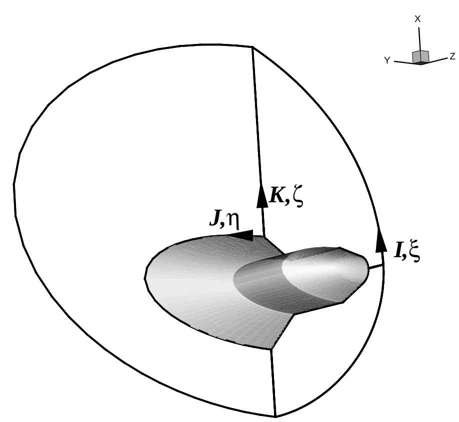


Figure 1: Grid-point coordinate and computational coordinate orientation.

Vehicle Parametric: Volume Grid Generation Method

The procedure for vehicle parametric volume grid generation utilizing elliptic solvers is as follows:

1) Isolate the portion of the volume grid that encompasses the geometrical feature to be modified.
2) Redistribute the interfaces of the isolated grid to the original volume grid to reduce the clustering in the K-direction.
3) Construct a new wall surface geometry which reflects the desired parametric change using CADCAM tools, and replace

the original surface in the isolated grid with the new surface.

4) Modify other faces affected by the change in geometry and interface surface grids.

5) Apply an elliptic solver to the volume grid (i.e., parametric zone).

6) Redistribute the grid points along the K-lines of the parametric zone volume grid to approximate the distribution in the original volume grid.

7) Insert the parametric zone volume grid back into the original volume grid, and blend the grid point distributions of the new grid to the original grid at their interfaces along the K-lines.

These individual steps are discussed in the paragraphs which follow.

Step 1: The portion of the volume grid which will be modified must be defined. The flow should be predominantly supersonic across its inflow interfaces and other outflow boundaries to minimize the need to recompute the CFD solution upstream of the geometry change. Further, bounding surfaces that extend from the wall to the outer domain should not lie along strong surface discontinuities at the wall. This second criteria will be explained later.

Step 2: The six faces for this modification region are extracted from the full grid to form an isolated volume grid (i.e., parametric zone), as illustrated in Fig. 2. Usually, the interface surfaces exhibit tight grid-point spacing (e.g., clustering at the wall), and large grid-point spacing at the outer domain in the K-direction. Such large variations in cell sizes are not conducive to rapid elliptic grid generation since the stiffness of the problem is proportional to the ratio of the largest and smallest cells.[11] To reduce such difficulties, the interface surface grids are redistributed to minimize cell volume variation. Eq. 1 is used to find a linear progression growth factor σ, such that the total arc-length in the wall to outer boundary direction is conserved;

$$\Delta S_{\text{new}_\zeta} = \Delta S_{\text{new}_{\zeta-1}}\sigma \qquad (1)$$

where,

$$S_{new_\zeta} = \sum_{\zeta=2}^{\zeta=\zeta_{\max}} \Delta S_{new_\zeta} = \sum_{\zeta=2}^{\zeta=\zeta_{\max}} \Delta S_{\text{old}_\zeta} = S_{old_\zeta}$$

and,

$$\Delta S_\zeta = \sqrt{(x_\zeta - x_{\zeta-1})^2 + (y_\zeta - y_{\zeta-1})^2 + (z_\zeta - z_{\zeta-1})^2}$$

The first cell size should be chosen so that all K-lines on an interface grid approach a value of $\sigma > 1$

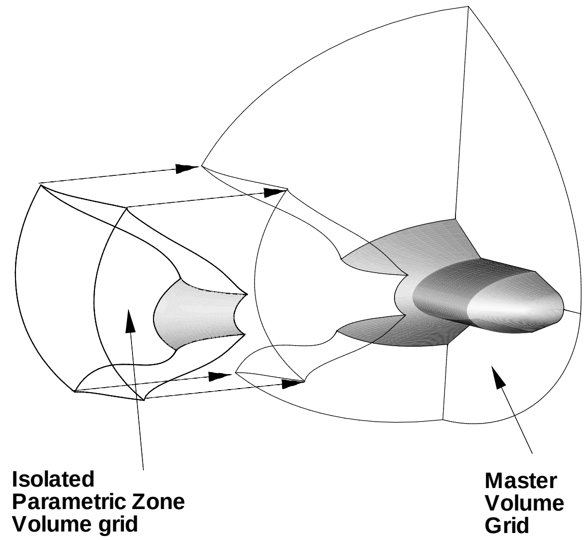


Figure 2: Extraction of isolated volume grid encompassing vehicle parametric change.

which yields clustering near the wall. Note that $\sigma < 1$ yields clustering at the outer boundary, while $\sigma = 1$ yields an equal distribution. The value of σ can be computed using a bi-section or Newton-Raphson method. Unfortunately, there may be instances where a value of $\sigma = 1$ will not produce smooth grid lines in the I- and J-directions, such as a discontinuity or large surface curvature gradient along a line of constant I. Usually the lack of smoothness in these grid lines can be corrected by varying the initial cell height, ΔS_{old_2}. In either case, the interface boundaries that extend from the wall to the outer boundary can be redistributed to enable elliptic smoothing. Fig. 3 illustrates a representative I_{min} interface before and after redistribution.

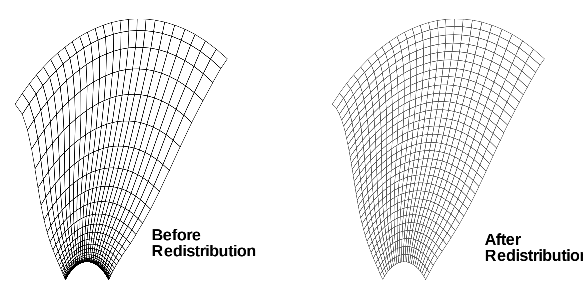


Figure 3: I_{min} interface grid redistributed to simplify elliptic volume grid generation.

Step 3: The new wall surface geometry for the isolated region is created. Typically, the surface geometry is generated with a Computer Aided Design (CAD) tool. The grid is attached to the surface with a grid generation tool, such as GRIDGEN[12] or ICEMCFD,[13] by projecting the interior points of the original surface grid to the new surface geometry. The projection of the old grid to the new surface decouples dependency of the new geometry surface types to the original geometry surface type. Hence, different techniques can be used to develop new geometry surfaces as opposed to the original techniques used.

Step 4: After inserting the new parametric wall grid, any other faces affected by this change in geometry need to be modified. Fig. 4 illustrates a case where a single additional face of the isolated volume grid requires modification. The other faces are unaffected by the geometry change. The regeneration of the faces is usually done using the GRIDGEN software.

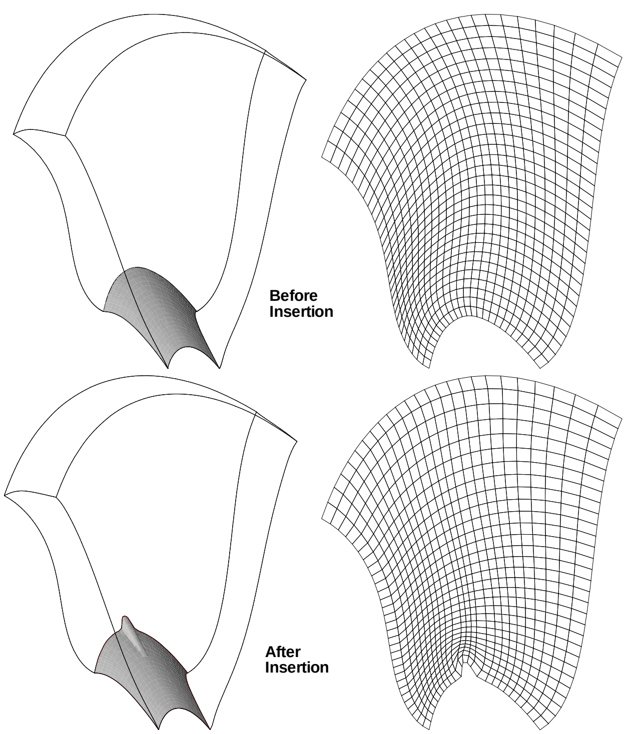
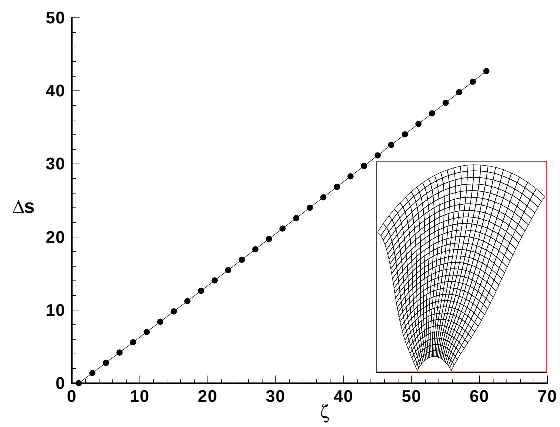


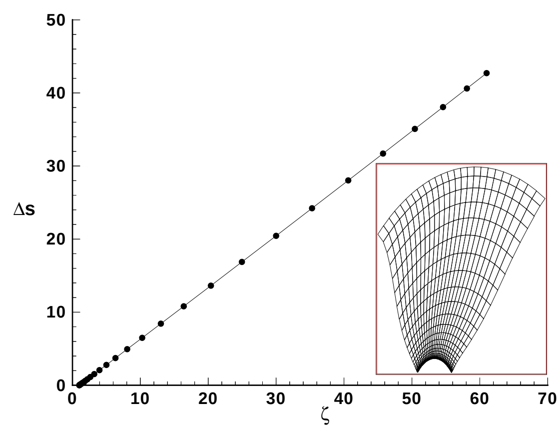
Figure 4: Insertion of design parametric and regeneration of an affected surface.

Step 5: The isolated volume grid is generated using the 3DGRAPE/AL[14] code. This code allows control of grid-line incidence angles, as well as cell heights at the block faces. Here, the incidence angle distributions for each face are defined from the original grid. By mapping the new surface grids to the old surface grids, the incidence angles of each point of the original interface can be interpolated onto the new surface grids. The interpolation is done using the grid computational coordinates transformed to arc-length parameter space.[15] The resultant grid lines of the isolated volume grid will smoothly merge with those of the original grid.

Step 6: The grid points along K-lines are redistributed in the parametric zone volume grid. This redistribution in the K-direction is accomplished through a parametric mapping of the grid lines, as shown in Fig. 5. The mapping transforms the physical domain, which has uneven spacings, to the computational domain where the points are equally spaced. Using Vinokur's[16] distribution function (a cubic or sine function may also be used), the computational coordinates



(a) Elliptically generated volume grid before parametric redistribution.



(b) Elliptically generated volume grid after parametric redistribution.

Figure 5: Parametric mapping of K lines before and after parametric redistribution.

are redistributed so that there is clustering at the solid wall surface. Interpolation of the clustered computational grid points back to the physical domain produces a grid point distribution in physical space that maintains the characteristics of the original grid (see Fig. 5). The distribution function requires a beginning cell size and, for some functions, an ending cell size. The beginning cell size for each K-line may be defined using the ratio between the cell sizes of the original and isolated volume grids, at the surface. As such, the new isolated parametric zone volume grid will have similar grid point distributions along the K-lines.

Step 7: The parametric zone volume grid is inserted into the original volume grid. Although the redistributed isolated grid may have similar grid-point spacing, a mismatch typically exists at the interface boundaries, as shown in Fig. 6. A blending region is

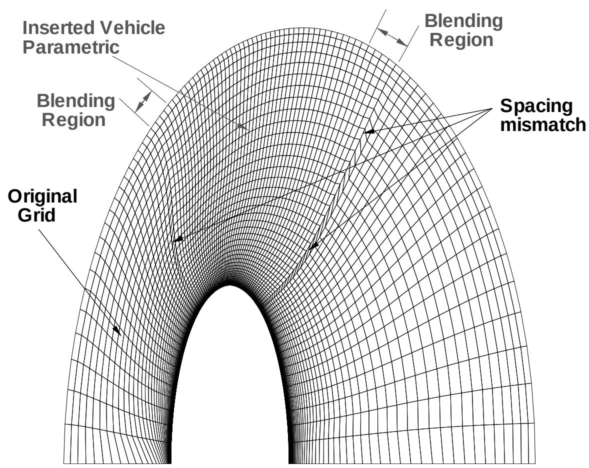


Figure 6: Redistributed vehicle parametric volume grid inserted into the original volume grid with blending regions identified.

employed to smooth this mismatch by blending from the interface boundaries across several points within the parametric zone volume grid. Usually, a ten-point region within the perimeter of the parametric zone volume grid is sufficient. The blending function for the I-direction is:

$$P(\xi) = P_0\left[\frac{(\xi_{\max}-\xi)^2}{(\xi_{\max}-\xi)^2 + (\xi-\xi_{\min})^2}\right] + P_1\left[\frac{(\xi-\xi_{\min})^2}{(\xi_{\max}-\xi)^2+(\xi-\xi_{\min})^2}\right] \tag{2a}$$

while the function for the J-direction is:

$$Q(\eta) = Q_0\left[\frac{(\eta_{\max}-\eta)^2}{(\eta_{\max}-\eta)^2 + (\eta-\eta_{\min})^2}\right] + Q_1\left[\frac{(\eta-\eta_{\min})^2}{(\eta_{\max}-\eta)^2+(\eta-\eta_{\min})^2}\right] \tag{2b}$$

These functions smoothly vary the scaling parameter P from P_0 (a cell size at the beginning of a region) to P_1 (a cell size at the end of a region) in the ξ- or I-direction, and Q from Q_0 (a cell size at the beginning of a region) to Q_1 (a cell size at the end of the region) in the η- or J-direction (see Fig. 7). These rational functions are elliptic in form, and produce a grid which is $C^{(2)}$-continuous across the interface from the isolated parametric volume grid to the original volume grid.

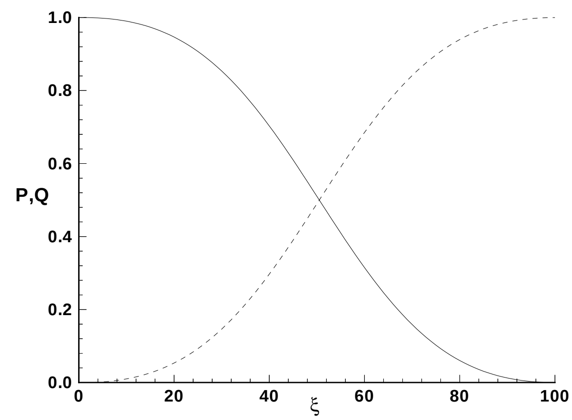


Figure 7: Blending functions P and Q for transitioning between inserted and original volume grid K-lines for $\xi_{\max}$=100.

To utilize these functions, normalized grid-point distributions between the interfaces and the tenth I- or J-plane in the interior of the parametric zone volume grid are blended in the I-, J-, or I- & J- directions. The latter directional blend is based on the product of P and Q for the I, J region. The product of P and Q is obtained by first blending with P and then with Q. The regions to which P and Q are applied are illustrated in Fig. 8. Therefore, use of the blending functions in equations 2a for the I-direction and 2b for the J-direction will produce a smooth transition from the interface of the original volume grid to points inside the parametric zone volume grid, as shown in Fig. 9.

Application of Each Method

A Single Stage-to-Orbit Vehicle (SSV), depicted in Fig. 10, will be used to illustrate this method. The design parametrics being sought are deflections for the pitch control surfaces (body flap and elevon). The domain to be modified is shown in Fig. 11. Fig. 12 shows

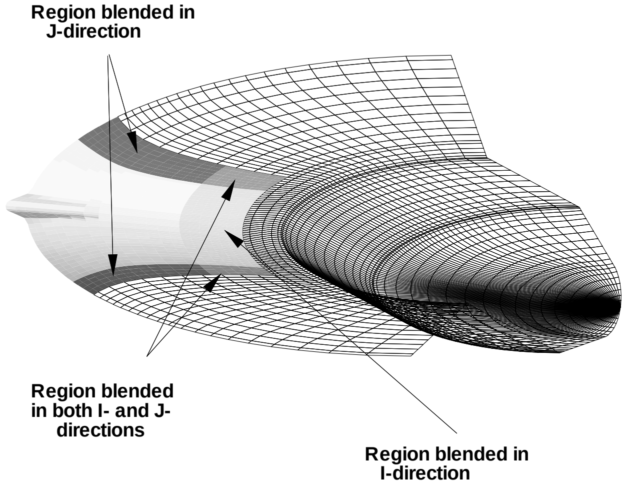


Figure 8: I and J regions identified for blending the parametric zone volume grid into the original volume grid.

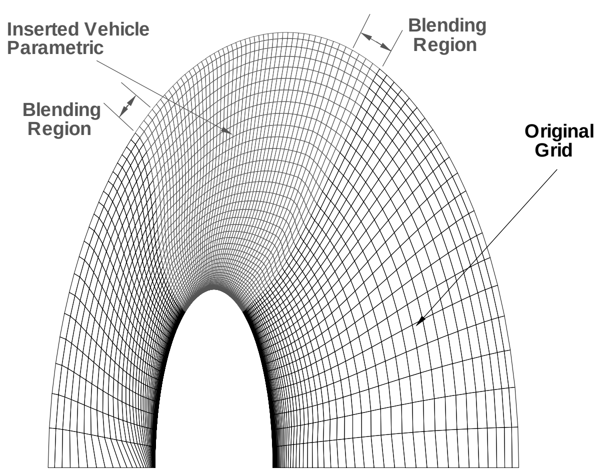


Figure 9: Representative I- plane after blending, via equation 2a.

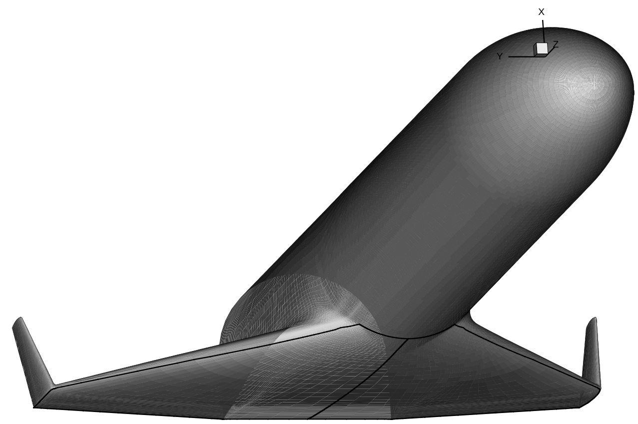


Figure 10: Single Stage-to-Orbit Vehicle used to illustrate vehicle parametric volume grid generation method, with accompanying identification of region to be changed.

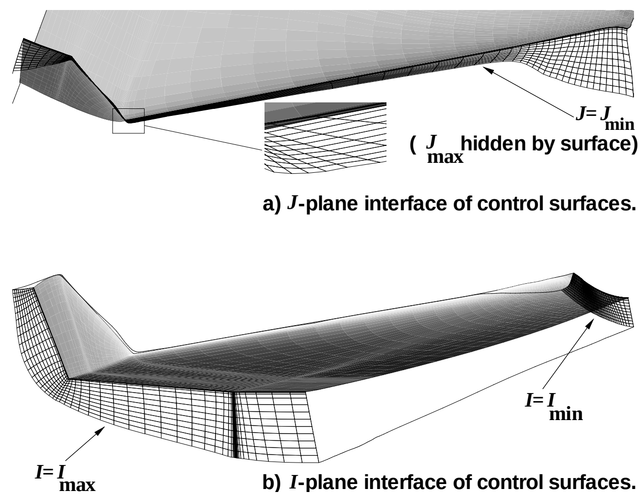
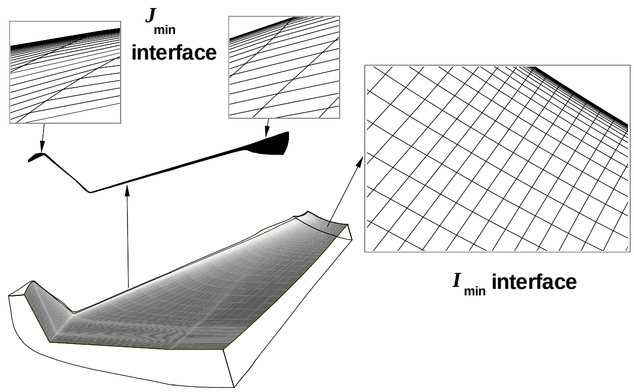


Figure 11: SSV body flap and elevon parametric region with, body to shock faces identified.

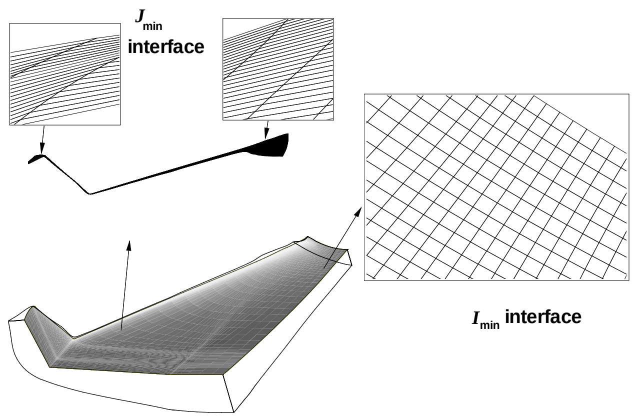
how the grid-point distributions on the interfaces were modified to facilitate elliptic smoothing. A new surface grid was generated to supplant the original surface description. Next, the I_{max}- and J_{max}-faces were modified to accommodate the redistributions of the I_{min} and J_{min}-faces, as shown in Figs. 13 and 14. A new outer boundary is created to complete the set of six faces for the isolated volume grid. The parametric zone volume grid was created with a 3-D elliptic solver, with continuity across all interfaces and orthogonality on the other faces. The resultant volume grid was redistributed, inserted into and blended with the original full body volume grid. Before and after results for the sample I- and J-stations are shown in Figs. 15 and 16, respectively.

The isolated volume grid is orthogonal to the wall surface and its grid lines smoothly approach those of the original grid across the interface boundaries. These qualities help minimize further grid adaption, as well as iterations of the flowfield solver, and allow CFD to be used in a parametric study environment.

The entire process was completed in 8 wall clock

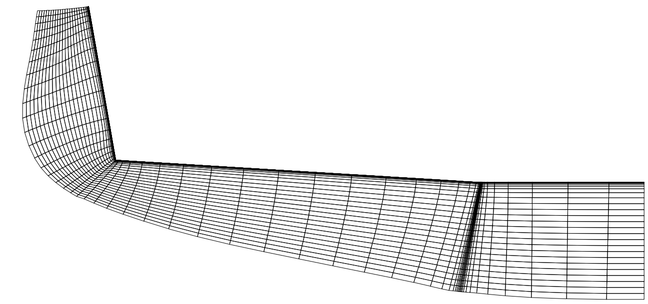


(a) Original grid distribution.

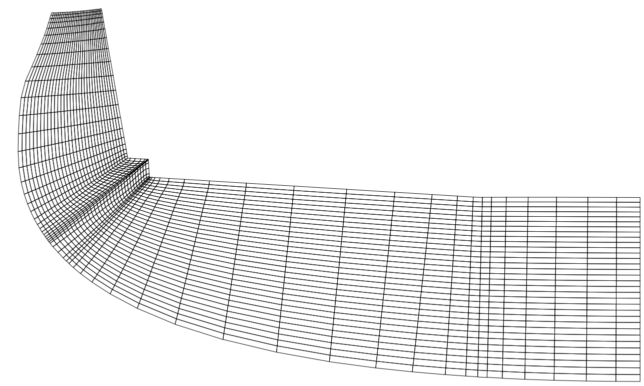


(b) Modified distribution.

Figure 12: Original and modified distributions for faces of parametric region.



(a) Original grid.



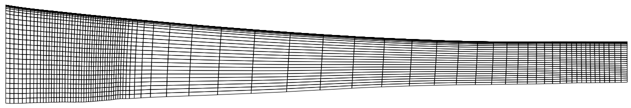
(b) New distributed grid with parametric inserted.

Figure 13: Exhaust plane (I=$I_{\max}$) for the parametric volume grid, thinned in K direction for clarity.

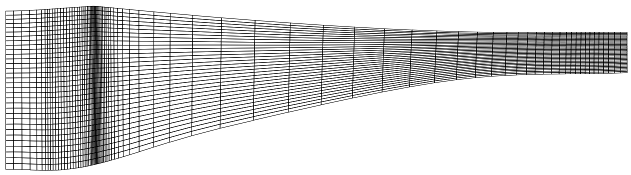
hours, including 4 CPU hours, using an SGI ONYX with 2-R8000 CPUs (Central Processing Unit). The breakdown is as follows:

- isolation of the parametric volume grid and redistribution of the interfaces grid points—1.0 hour wall clock and .5 hour CPU;
- insertion of the new surface grid and generation of the exhaust face—1.25 hours wall clock and 0.5 hour CPU;
- computational time for volume grid generation—1.25 wall clock and 2.5 hours CPU;
- restoration of original grid-point distribution, insertion into original volume grid, and blending with original grid—0.5 hour wall clock and 0.5 hour CPU.

Past experience[17] has shown that the traditional approach of blending in the design parametric and regenerating the entire volume grid requires an equivalent amount of wall clock time but an order of magnitude greater amount of CPU time.



(a) Original grid.



(b) New distributed grid with parametric inserted.

Figure 14: Windside symmetry plane (J=$J_{\max}$) for the parametric volume grid, thinned in K direction for clarity.

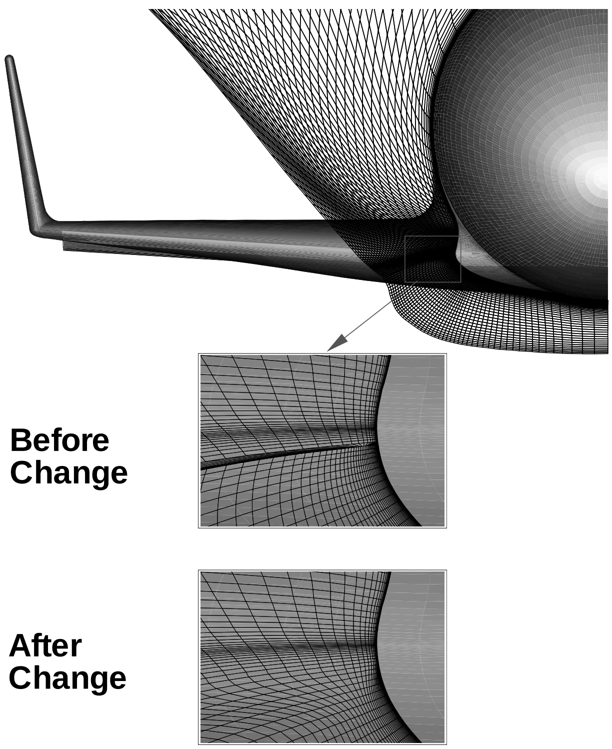


Figure 15: Example I-station from full volume grid, before and after parametric change.

Conclusion

Present day methods used to modify aerodynamic configurations usually require development of entire volume grids about the vehicle. This is very time consuming and inefficient. A method for generating vehicle parametric volume grids for viscous CFD simulations using a zonal approach is presented in lieu of current methods. This robust approach incorporates simple algebraic techniques of redistribution to aid in the elliptic generation and smoothing of the isolated volume grid, reducing the amount of required CPU time to generate the new volume grid by an order of magnitude. This method accepts generalized surface definitions since the surface representations are decoupled from the surface grid generation. Robustness also arises from the capability to blend the parametric zone volume grid with the original grid. This method offers a fast and efficient volume grid generation and modification capability for CFD parametric studies. The approach maintains gridline characteristics within the isolated volume grid that are similar to the original volume grid and allows grid adaption to be used before and after application. Use of this technique allows CFD solvers to be used to augment wind tunnel testing in parametric studies, thereby reducing design time and probram costs.

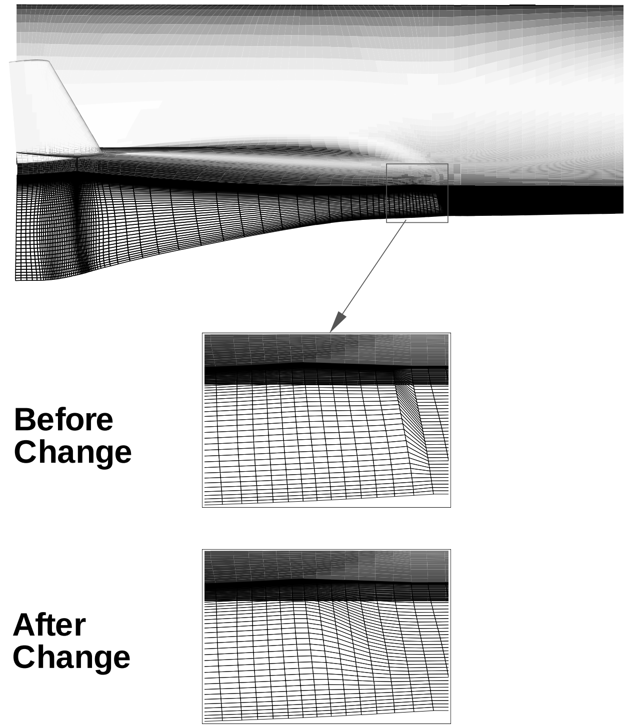


Figure 16: Example J-station from full volume grid, before and after parametric change.

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